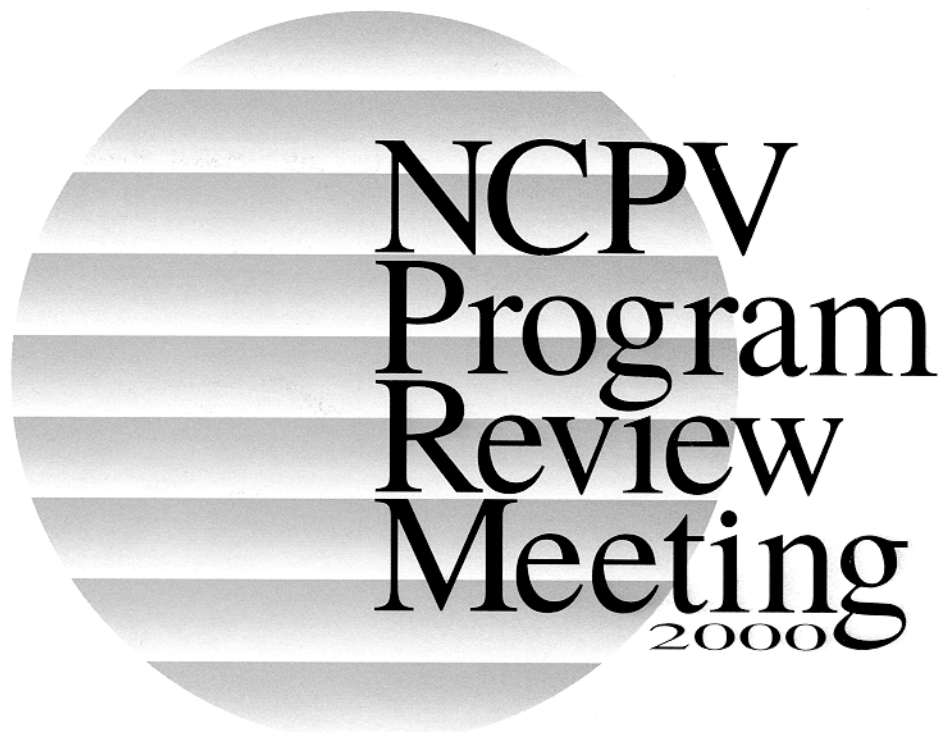


PROGRAM AND PROCEEDINGS



April 16–19, 2000

**Adam's Mark Hotel
Denver, Colorado**



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All Hot-Wire Chemical Vapor Deposition a-Si:H Solar Cells

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ABSTRACT

Efficient hydrogenated amorphous silicon (a-Si:H) nip solar cells have been fabricated with all doped and undoped a-Si:H layers deposited by hot-wire chemical vapor deposition (HWCVD). The total deposition time of all layers, except the top ITO-contact, is less than 4 minutes. On an untextured stainless steel (SS) substrate, an initial efficiency of 7.12% is reached, with a stable efficiency of 5.4% after 1000 hours 1 sun light soaking. This initial efficiency is reached by incorporating into the p/i interface about 60 Å of intrinsic a-Si:H "edge" material grown at conditions near the transition to microcrystallinity. As a result, the cell's fill factor increases from 0.60 to 0.68 and the best open-circuit voltage is about 0.88 V. Using textured Ag/ZnO-coated SS supplied by United Solar Corporation, preliminary cell fabrications on textured SS have given an all-HWCVD initial efficiency record of 8.7 %.

1. Introduction

Increasing the throughput of efficient hydrogenated amorphous silicon solar cell fabrication is an important issue relating to production costs. One method to increase the factory throughput is to increase deposition rates. The best plasma enhanced chemical vapor deposition (PECVD) a-Si:H solar cells are currently fabricated at a deposition rate of about 1 Å/s, giving a total fabrication time of about 40 minutes (2300 Å i-layer). Increasing the deposition rate beyond 1 Å/s has been attempted using PECVD [1] at 3-6 Å/s and HWCVD [1,2] at 18-20 Å/s. High deposition rates, in general, will reduce the device performance.

One of the advantages of HWCVD is the high deposition rate, not just for the intrinsic layer (i-layer) but also for all other dopant layers. In previous "hybrid" HWCVD solar cell research, all the dopant layers (n- and p-layers) were deposited by PECVD at about 1 Å/s and the i-layer by HWCVD at about 20 Å/s. For such "hybrid" solar cells, the throughput has already been increased by about a factor of 10 compared to those of PECVD devices, since the i-layer is by far the thickest device layer. However, when depositing all layers by HWCVD, the already shortened deposition time can be further reduced. In this work we describe the fabrication and properties of all-HWCVD a-Si:H nip solar cells made in less than 4 minutes, compared to the "hybrid" HWCVD cells with a total deposition time of 17 minutes.

2. Experimental and Results

A two-chamber load-locked system was used to fabricate all-HWCVD nip solar cells. One chamber (i-chamber) is used only for intrinsic a-Si:H deposition. The other chamber (dopant chamber) is used to grow the "edge" materials (e-layer) and both n- and p-type dopant layers. The details of this HWCVD reactor are reported elsewhere [3]. In both chambers, we use a spiral tungsten wire with a diameter of 0.5 mm, a length of 24 cm, and place it 5 cm below the substrate. The tungsten filament is heated to about 2000°C using an AC current. A process gas passes by the hot filament, dissociates on the filament, and leads to Si/H deposition on the substrate. With the aid of the load-lock chamber, the substrate can be transported without an air break between the two deposition chambers, thus ensuring the production of atomically clean interfaces.

The solar cell is deposited on a SS substrate with the structure SS/niep/ITO, where "e" denotes "edge" material. The n-layer is first made in the dopant chamber at a substrate temperature (T_{sub}) of ~300°C. The substrate is then transferred to the i-chamber for i-layer deposition at a T_{sub} of 320° to 360°C. Finally, the substrate is transferred back to the dopant chamber for e-layer and p-layer deposition at T_{sub} of 200°C. The thickness of each layer in a solar cell (see Table I) is estimated from the deposition rate of each layer grown on a glass substrate under the same deposition conditions. The top contact is 600 Å of indium tin oxide (ITO) deposited by reactive thermal evaporation, typically with a sheet resistance of 100 ohm/sq and 87% transmittance. The solar-cell performance is measured with a computer-interfaced JV station (XT-10) under 1-sun illumination (Xenon lamp). Light soaking of the solar cells is made under a 1- sun ELH light source.

We now describe the properties of the individual solar cell layers, which have been first evaluated using (thicker) films on glass or c-Si substrates. For the a-Si:H n-layer, PH_3 (3% in H_2) is used as the dopant gas which is mixed with SiH_4 . Good n-layer properties with a conductivity of 2×10^{-2} S/cm and optical gap (E_{04}) of 1.88 eV are easily achieved with a high deposition rate of 11 Å/s. Also, the growth conditions for obtaining such good properties are quite broad. The film thickness used for the evaluation is about 2000 Å. The characteristics of HWCVD growth of a-Si:H are high T_{sub} (320 to 360°C), low pressure (12 mT), and high deposition rate (18-20 Å/s) when compared to PECVD. Typical properties of this HWCVD i-layer are an

E_{04} of 1.89 eV, a low H-content of 3% to 6%, a low saturated defect density of 2 to 4 $\times 10^{16}$ (cm⁻³), a dark conductivity $< 10^{-10}$ S/cm, and a conductivity ratio (1-sun to dark) $> 10^5$. The film thicknesses used for these evaluations are between 0.5 and 1 μ m.

The "edge" materials near the transition from a-Si:H to μ c-Si are made using high hydrogen dilution [4-8]. The film thickness used for the evaluation is about 2000 Å. Extensive measurements of material properties have been published elsewhere [9-11]. The phase (a-Si:H or μ c-Si) of these materials can be easily determined from x-ray, Raman, or UV-reflectance spectroscopies. The structure and most of the properties of these materials are still a-Si:H like. The optimum growth conditions of these materials depends not only on the deposition parameters, but also on the film thickness and choice of substrate. It is worth noting that a-Si:H turns into μ c-Si at the H₂ to SiH₄ ratio of 2 to 3 on a glass substrate when using HWCVD. This dilution is much lower than the transition ratio in PECVD, probably because a large amount of atomic hydrogen is generated by the filament during silane decomposition. The deposition rate of this edge material is 4 Å/s. Finally, for the HWCVD p-layer, TMB (5% in He) gas is used as the dopant gas. With an H₂ to SiH₄ ratio of 16, a series of p-layers was made by varying the TMB flow rate from 1 to 7 sccm. The film is μ c-Si when the TMB flow is less than 3 sccm and turns to a-Si:H when the flow is greater than 4 sccm. The TMB flow we used was 6 sccm.

Table 1. Comparison of all HWCVD to "hybrid" devices

Layers	All-HWCVD phase•thk. •time•rate	"Hybrid" (HW- & PECVD) phase•thk. •time•rate
n	a-Si•200Å•20s•10Å/s	* a-Si•400Å•4m•1.7 Å/s
i	a-Si•2500Å•2.5m•20 Å/s	a-Si•2500Å•2.5m•20 Å/s
Interface	edge-Si•60Å•15s•4 Å/s	* H ₂ Plasma•10min
p	edge-Si•130Å•30s•4.3 Å/s	* a-Si•100Å•1min•1.6 Å/s
Tot. Time	3.5 min	17.5 min

* = PECVD layers

Turning now to the solar cell results, Table 1 lists the material phase, thickness, deposition time, and deposition rate of all solar cell layers for the present all-HWCVD solar cell as well as the "hybrid" solar cell. As can be seen, our all-HWCVD solar cell takes advantage of the high deposition rate, and we achieved 3.5 minute total deposition time for all the layers that contain Si. It simplifies the process procedure by replacing the 10 minute PECVD H plasma treatment with a 15 second HWCVD e-layer deposition.

Table 2. HWCVD Solar Cell Performance on flat SS

Cell Type	LS State	V _{oc} (V)	FF	J _{sc} (mA/cm ²)	Eff.
All-HW	Initial	0.877	0.688	11.90	7.19
	1000 hr	0.817	0.572	11.74	5.48
Hybrid (HW-PE)	Initial	0.850	0.666	10.21	5.74
	1000 hr	0.830	0.572	10.20	4.86

Table 2 summarizes the best performance of both HWCVD nip solar cells on untextured, bare SS substrates. The best all-HWCVD cell has an initial efficiency of 7.19% with a V_{oc} of 0.88 V, a FF of 0.688, and a J_{sc} of 11.9 mA/cm². The best efficiency after 1000 hours 1-sun light soaking is 5.48%. When compared to the "hybrid" cell, the all-HWCVD cell demonstrates an improvement in all the initial cell performance parameters. We transferred the best recipe to a textured Ag/ZnO back-reflector substrate supplied by United Solar Corp., and obtained an all-HWCVD record initial efficiency of 8.7 %.

3. Summary

Efficient high throughput all-HWCVD a-Si:H nip solar cells have been demonstrated. All layers that contain Si were finished within 4 minutes. This reduction results from reducing the n-layer and p-layer deposition times as well as replacing a long PECVD hydrogen treatment at the p/i interface with a short deposition of "edge" a-Si:H layer material. Applying this e-layer to HWCVD solar cells is the key to the improvement of cell efficiency. Initial efficiencies of 7.12% and 8.7% were reached on untextured and textured SS substrates, respectively.

4. Acknowledgements

Authors would like to thank J. Yang and S. Guha at United Solar Inc for invaluable help. This work is supported by DOE subcontract DE-AC02-83CH10093.

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